

MEMS IN SPACE SYSTEMS

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Abstract

Microelectromechanical Systems (MEMS) provide an emerging technology area that has the potential for revolutionizing the way space systems are designed, assembled, and tested. The high launch costs of current space systems are a major determining factor in the amount of functionality that can be integrated in a typical space system. MEMS devices have the ability to increase the functionality of selected satellite subsystems while simultaneously decreasing spacecraft weight.

The Air Force Phillips Laboratory (PL) is supporting the development of a variety of MEMS-related technologies as one of several methods to reduce the weight of space systems and increase their performance. MEMS research is a natural extension of PL research objectives in microelectronics and advanced packaging. Examples of applications that are under research include on-chip microcoolers, micro-gyroscopes, vibration sensors, and three-dimensional packaging technologies to integrate electronics with MEMS devices. The first on-orbit space flight demonstration of these and other technologies is scheduled for next year.

Introduction

PL research in the Space Electronics Division (PL/VTE) is dedicated to solving pacing problems in existing and emerging USAF space systems. Chief among these problems is the need to provide high density electronics solutions that are within the cost, reliability, and performance requirements of these systems. While much of the PL/VTE research investment is devoted to the development of radiation-hardened processes and components that are normally taken for granted as available by terrestrial systems (such as microprocessors and memory), significant development programs in advanced two- and three-dimensional microelectronics packaging have existed for nearly a decade. These programs initially were concerned with wafer scale integration of complex digital functions to accelerate the miniaturization benefits of radiation-hardened microcircuits, but later expanded in terms of the types of electronics addressed (e.g., analog, microwave, power) and in the approaches for achieving this reduction. Great benefits were later achieved through the exploration of three-dimensional packaging and the significant parallel investments by the Advanced Research Projects Agency (ARPA) in packaging technology in general. The greater density benefits of three-dimensional packaging led to more and more systems functions being addressed within very dense multi-chip modules (MCMs). Within the last five years, the advent of MEMS has promoted the possible integration of MEMS devices as well, leading to provoking systems engineering possibilities, such as enclosing inertial reference units (IRUs) within MCMs. One program, the monolithic interceptor processor (MiP), explored concepts for reducing the complete high-performance electronics system for an interceptor in smaller than a coffee cup (<25 cubic inches), complete with cryogenic imaging sensors and IRUs, and limited prototyping activities based around "many-layered" (>12) 3-D MCMs have been conducted. More recent research has evolved that may establish standards for heterogeneous 3-D packaging in electronic systems.

While PL's exploration of packaging issues had raised the possibility of introducing MEMS devices into systems to further accelerate the size, weight, and power reductions, a number of USAF Small Business Innovative Research (SBIR) projects and PL-sponsored Air Force Institute of Technology (AFIT) research efforts focus MEMS development activities in a complementary sense to provide solutions to certain packaging problems (thermal management) and miniature sensors (vibration sensors). Many innovative concepts that are discussed in this paper are products of these efforts.

Over the last few years, PL/VTE has worked more closely with the Aerospace Corporation, ARPA, and NASA to better define and establish solutions to barriers for the inclusion of MEMS devices in space systems. Aerospace has introduced the notion of Application-Specific Integrated Microinstruments (ASIM), a concept to which PL has contributed several packaging concepts, including the "Constant Floor Plan" MCM, which can greatly accelerate the schedule and reduce cost for early prototypes. Of the great variety of ARPA MEMS research initiatives, three efforts in particular have been identified in which PL provides technical management support. Among these are programs that involve micro-inertial reference systems, advanced micro-instruments, and failure analysis of MEMS devices. NASA's New Millennium Program (NMP) is pursuing a paradigm for satellites beyond 2000 that are not only much smaller than the present genre of civil and military satellites, but built in greater quantity, much more quickly, and at a much lower cost. The possibility of achieving these goals with MEMS was deemed to be so significant a possibility as to warrant NMP establishing an Integrated Product Development Team (IPDT) in MEMS and Instruments, one of only five for the entire initiative. PL/VTE is involved as a member on that IPDT, as well as the microelectronics IPDT, to support the establishment of technology roadmaps to achieve ambitious NMP objectives.

In research to date, one of the most significant barriers encountered to the spaceflight of MEMS devices is a perception (sometimes correct) of technology immaturity. Intrinsically, lack of reliability data on MEMS devices are indicated, particularly in a space environment. The lack of real data on MEMS performance in space environments has been so acute as to promote the development of dedicated experiment and sub-experiment payloads for space missions as an in-house activity in PL/VTE. At least two space experiment payloads with dedicated MEMS devices and objectives are under development at the time of this writing, with prospects of three other experimental missions within the next five years. In each case, a search has been underway to identify the most current relevant and useful examples of MEMS devices that are suitable for spaceflight. In fact, the first two experiments do not contain products of PL/VTE MEMS research programs, since some commercial devices, such as accelerometers, have emerged that are slated for widespread use in the automotive industry. The search continues, with plans to field the most promising candidate of PL/VTE, ARPA, NASA, and commercial MEMS research.

MEMS Programs

This section describes several of the aforementioned MEMS research efforts which are directly relevant to space and missile applications. Many MEMS efforts have been established to find better solutions to advanced packaging of electronics, particularly in the efficient thermal management of 3-D densely packaged MCMs. Active thermal management solutions, ranging from microcoolers with flow-through liquids and pumps to Sterling engine refrigerators are being explored. Another class of MEMS efforts deals with packaging issues associated with MEMS devices. One MEMS research effort, sponsored at AFIT, deals with the compatibility of canonical MEMS structures with representative types of MCM packaging approaches. In a second effort, a 3-D packaging approach is being explored for inclusion of certain MEMS components. Another class of MEMS device research deals with MEMS-based relays which is quite important to space systems. Finally, other MEMS efforts pertain to the establishment of an instrumentation (sensing) function, such as vibration, linear, or rate sensors, in particular for tactical grade inertial measurement.

Thermal Management of Advanced Packaging

It is intuitively clear that as electronics functional densities increase, so too does power density and power dissipation per unit volume. Given that a conventional system achieves a real packaging efficiency of less than one percent, it is not surprising that a thermal management issue might exist when the same electronics are packaged at > 25% efficiency, as in the case of some more recent PL/VTE packaging research. Thermal management has been found a natural role of MEMS technology. The diversity of MEMS approaches to achieve thermal control is quite impressive.

Micro-Encapsulated Liquid Cooling. Two AFIT research efforts^{1,2} were sponsored to investigate the benefits of silicon micromachining to the thermal management problem of planar MCMs. These efforts were based on an approach of a plenum system formed directly into silicon wafers through micromachining. A number of configurations and microtextures were examined for thermal performance under various gas and liquid flow-through conditions. The circulating liquid, supplied from a peristaltic pump, in effect provided the effect of an active heat spreader.

The concept of directly micromachining silicon wafers to form thermal management structures was also applied in the second phase of a PL-managed USAF SBIR research program³ to form an efficient indirect cooling system for distributing liquid nitrogen to a nine-chip prospective MCM based on cryogenic digital semiconductors and multilevel high temperature superconducting interconnections (Intermagetics General Corporation, Albany, NY). In this case, deep microchannels are formed through a special chemical process to positions of a silicon wafer corresponding to each of nine chip locations. Liquid nitrogen flow-through with this configuration, depicted in simplified form in Figure 1, achieves a more effective cooling system than direct immersion.

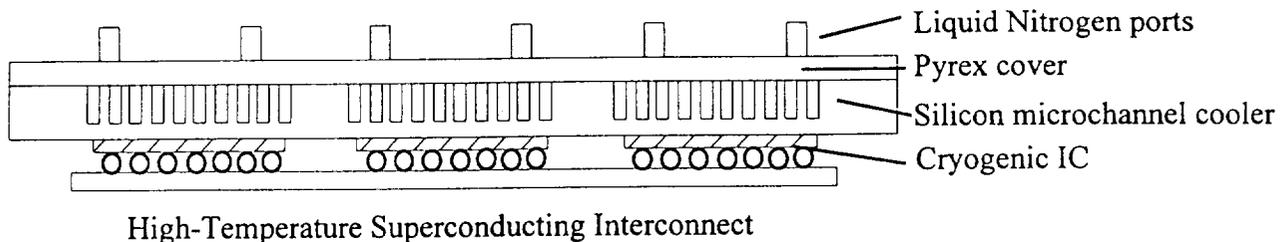


Figure 1. Simplified depiction of microchannel cooler for cryogenic thermal control.

Miniature refrigerators for ICs. Another more direct approach for cooling heat-generating components involves the application of micromachining and micro-engineering technology to create miniature refrigerators, about the size of an IC (one cm²). An on-going phase II SBIR is investigating the construction of components for such refrigerators based on a Stirling engine, with the goal of cooling heat generating components which normally operate at ambient temperatures (Sunpower, Athens, OH)⁴. A prospective application of such a Sterling cooler involves its strategic placement within locations of MCMs that contain several high-power integrated circuits, in a manner transparent to the end user.

Compatibility of MEMS in Packaging Approaches

Without adequate attention to packaging, MEMS devices lose their full potential to reduce the size, weight, and power of systems. Packaging of MEMS with other components in MCMs logically exploits the benefits of both approaches. A three-dimensional approach to combine certain MEMS devices that employ a simple flip-chip approach is under development based on a "telescopic" stacking of monolithic devices (Optical ETC, Huntsville, AL) to realize a multi-chip assembly. This investigation is supported as a SBIR program funded by the Technology Reinvestment Program⁵. A PL-sponsored AFIT PhD research effort is in progress to investigate the compatibility of various MEMS

devices with thin-film MCM processes. At issue is the sequence of fabrication to realize practical MCMs that contain MEMS devices. Handling MEMS devices after release chemistry steps is often problematic, but performing release chemistry on an ensemble of non-MEMS chips may also be difficult. The approach explored in this effort will create a sort of MEMS-based assembly test chip (ATC), similar to MCM ATCs developed by Sandia National Laboratories for packaging and assembly process condition monitoring.⁶ By introducing this ATC into a packaging system, it will be possible to explore the impacts of the fabrication sequence on the MEMS devices as well as examine a typical release process on the MCM or assembly.

Micro-relays

Microrelays have significant potential to improve reliability and performance in space systems. Electro-mechanical relays are generally undesirable in conventional form for space systems due to their bulkiness and potential for failure. The simpler construction and use of tightly controlled batch fabrication processes may result in relays that have better reliability and that may be aggregated to facilitate graceful degradation. Other fault tolerant concepts possible for such devices, by their compact nature, include their use in creating densely packaged, switchable buses for complex spaceborne architectures. Solid state switches are not always adequate in space environments due to the tenet issues of the space radiation environment on semiconductors. Total ionizing dose effects degrade the salient characteristics of many bipolar and FET-based switching device processes, even for digital applications.

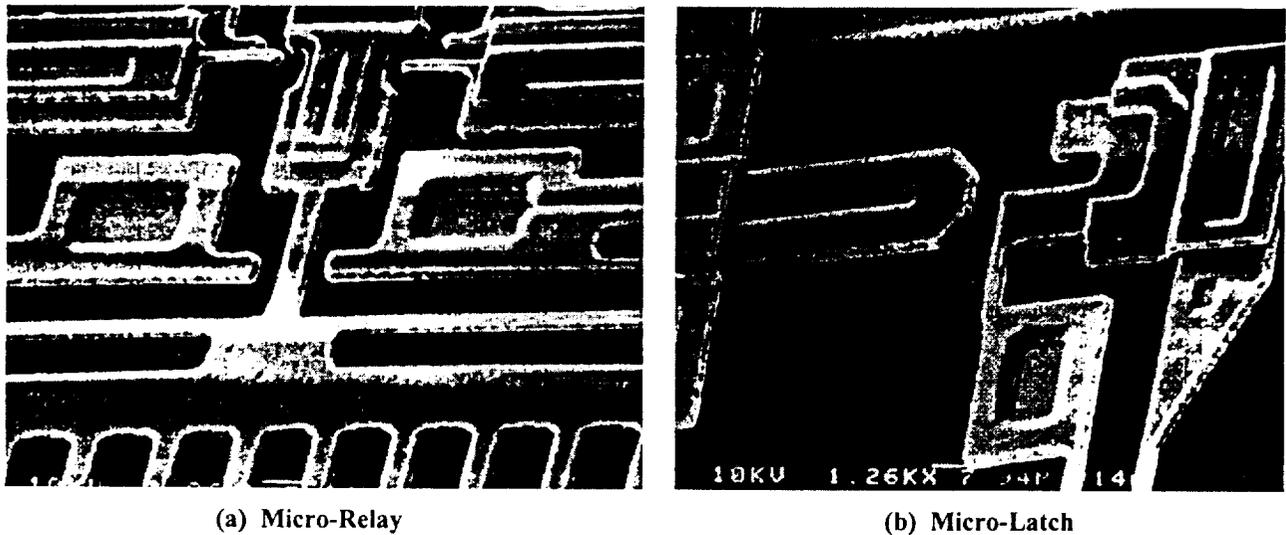


Figure 2. Micro-relay and micro-latch designed, fabricated, and tested at AFIT during 1994. (photographs provided courtesy of Dr. Victor Bright, AFIT Department of Engineering).

The inability to service space systems make attractive the possibility of incorporating on-board spare assemblies that are positively and physically “dis-connectable” from the system. Even the best conventional solid state switching devices cannot achieve this performance for the most sensitive instrumentation systems, due to small but finite leakage currents, the lack of signal excursion capability and dynamic resistance non-idealities. These approaches are also not possible with bulky conventional relays, but could be easily achieved with micro-relays. For power reduction, micro-latches (relays with memory) are also desirable. Various AFIT research projects have produced several designs of micro-relays and micro-latches for advanced MEMS switching techniques (Figure 2)⁷.

MEMS-based Motion and Inertial Sensing

Under ARPA sponsorship, Draper Laboratory is conducting a \$6M effort to design and build micro-inertial reference systems components using flip-chip bonding technology. A monolithically packaged rate sensor is shown in Figure 2 based on the Draper approach. It is conceivable that, when combined with MEMS-based accelerometers, a complete inertial reference unit based on three orthogonally mounted pairs of gyroscopes and accelerometers could be realized within one cubic inch.

An additional goal of the research is to produce low-cost MEMS inertial sensors by reducing the cost in two categories. First, the cost of packaging the devices is hoped to decrease with improvements in the stability of the gas environment and device alignment within the vacuum package. Additionally, it is desired to develop an integrated test process that would minimize cost by establishing an improved acceptance and calibration procedure during manufacturing.

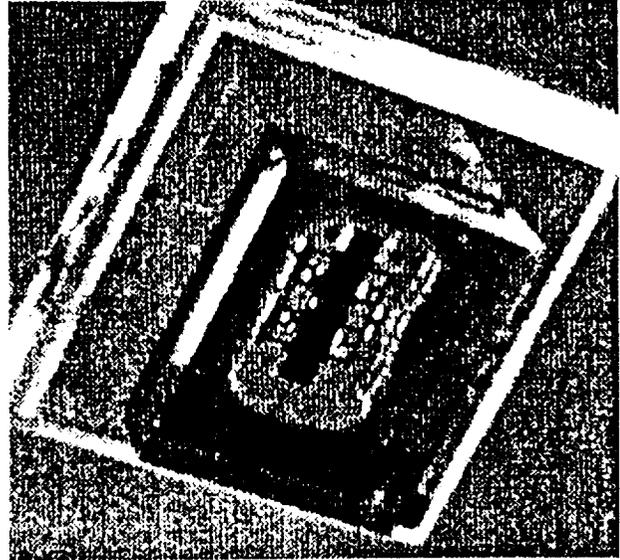


Figure 2. MEMS-based monolithic rate sensor.

Flat-Pack Gyro. In 1993, for the MiP study, a number of micromachined inertial sensors were examined, none of which possessed adequate drift rates. The search for better rate sensors, in

conjunction with a published solicitation for SBIR topics in MEMS, led to a very promising concept involving a spinning gyro rate sensor. The current effort, a second phase SBIR, involves a "milli-machined" version of a gyroscope of more conventional origin, in which the drift rate is reduced by several orders of magnitude over standard designs. A millimachined chip-size gyroscope is under developed that may theoretically achieve a 0.5 degree/hour drift rate. Shown in Figure 3, the gyroscope operates like standard gyros with a design variation that uses a spinning disk supported with gas bearings as the inertial reference. The disk is magnetically actuated and its motion is capacitively coupled to sensor electrodes that detect the output axis rotation.⁸

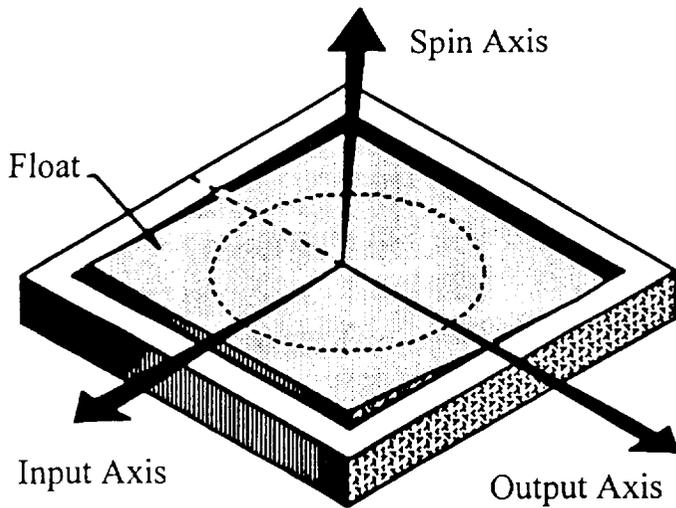


Figure 3. The Flat Pack Gyro (approx. one inch square).

Piezoresistive Vibration Sensor. A SBIR project is under way at InterScience, Inc. in Troy, New York in which an array of cantilever devices is used for vibration sensing. Each cantilever has a mass supported at the end of beams of various length throughout the array. The base of each cantilever is piezo-resistively coupled to a potential source that can detect the motion of the beams. The result is a real-time spectral vibration sensor that has a frequency resolution proportional to the difference in the lengths of adjacent beams.⁹

Micro-Instruments and Actuators

Certain MEMS devices, when combined with microelectronics and advanced packaging, can form microinstruments. One ARPA-funded project (under Broad Agency Announcement 94-40) of direct interest involves an approach to construct various scientific instruments such as gas chromatographs through the introduction of a novel pump concept (Berkeley Microinstruments, Menlo Park, CA). Joint discussions between Aerospace and PL/VTE have further identified an enabling concept for a customizable, common instrument MCM, for which the components are pre-defined, but the interconnects are user-definable. With this concept of a "constant floor plan" MCM (Figure 4), it is possible to realize rapidly prototype-able instrumentation electronics, to which sensors could be surface mounted. Clearly, this concept, combined with the aforementioned research in MCM-MEMS compatibility will significantly advance the ability to create more affordable application-specific integrated microinstruments.

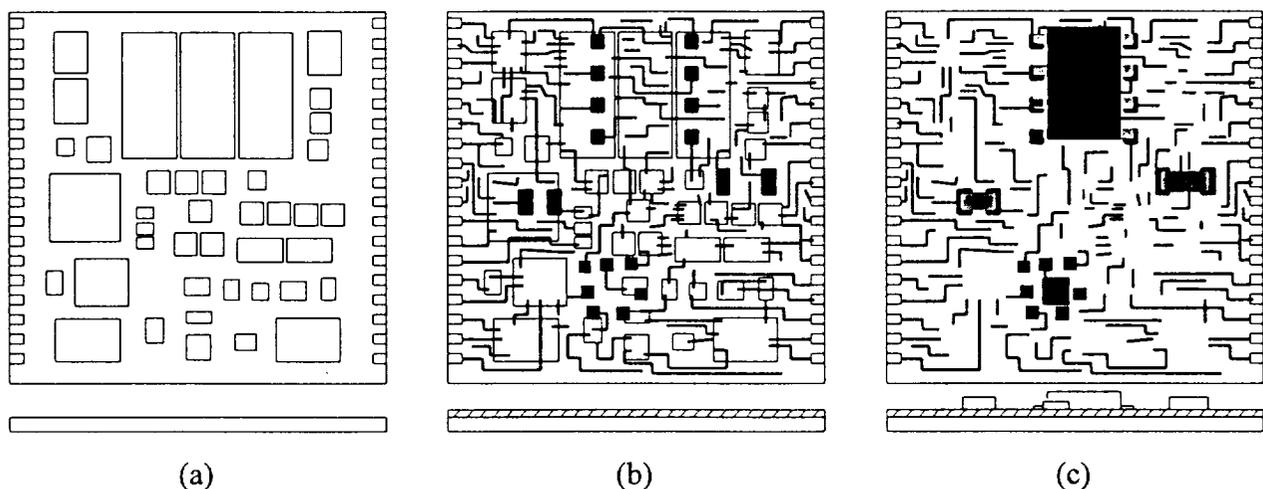


Figure 4. Constant Floor Plan rapid prototyping concept. (a) Substrate with pre-determined commodity component arrangement. (b) Formation of patterned overlay interconnection to chip bond pads and for surface-mount connections. (c) Introduction of MEMS sensor.

Deformable Micromirrors. Deformable micromirrors have tremendous promise to provide support for applications where dynamic adjustments of phase or angle in certain types of optical trains are required. Several groups within Phillips Laboratory have examined deformable micromirrors for a variety of applications. PL/VTE is planning research to explore micromirror arrays designed to function in a variety of tasks currently reserved for larger, heavier, and more costly equipment.

Two primary styles of micromirrors are under consideration for space systems applications. The first is the phase-mostly piston style flexure-beam device that can be employed for phase manipulation of optical data. This style of device is known for its applications in adaptive optics in which large arrays are individually actuated to discretely lengthen or shorten an optical path to correct for phase aberrations. Such phase aberrations are inherent in optical systems which must operate within or through the earth's atmosphere in which random discontinuities in atmospheric pressure, temperature, and density create discrepancies in propagation along the optical wave front. The use of such devices can extend the limit in resolution of current optical systems or allow space systems to use optical information processing.

Another design of micromirror under consideration is an Axial-Rotation device. This device, or a similar design, can be used to scan a field of view and send the optical information to an image sensor that can be rigidly placed in a space system. For instance, the tracking of ICBMs is typically done using a large gimballed mirror that is rotated around to select a field of regard. As an alternative, a chip

containing millions of micromirrors could be employed to perform this tracking and scanning function much more efficiently. A proposed plume acquisition system is shown in Figure 5. The approach is analogous to the High-Definition Television system developed by Texas Instruments. Rather than projecting an image, however, the imaging sensor is used to measure the relative infra-red intensity of an array of pixelized scenes from the field of regard¹⁰.

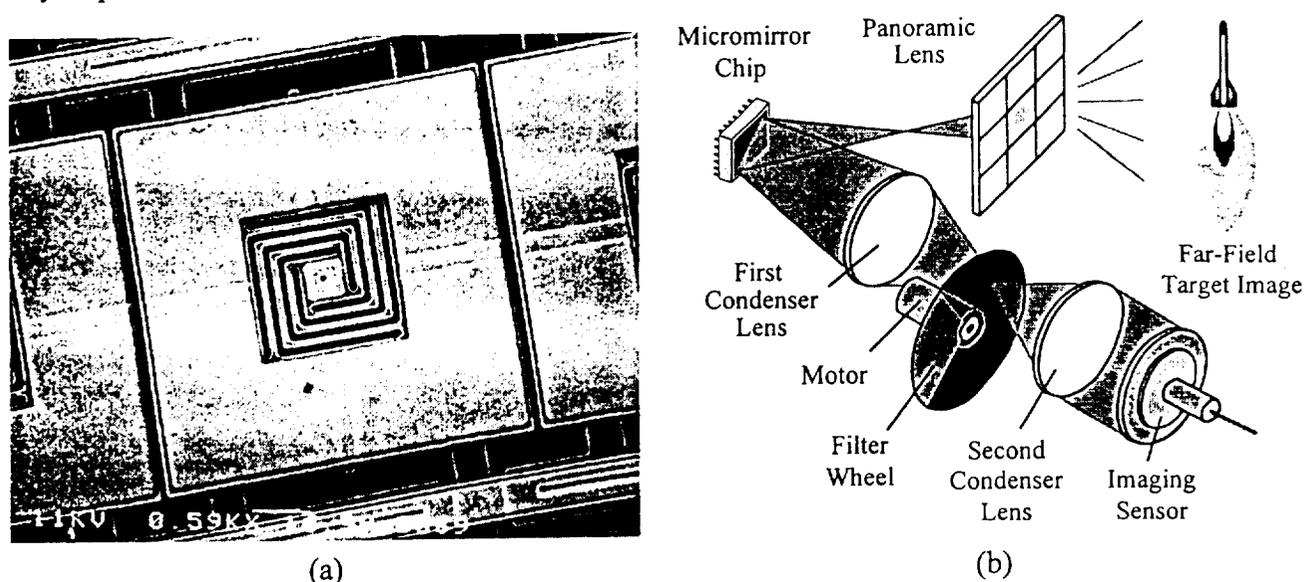


Figure 5. Axial-Rotation micromirrors and applications. (a) Micromirror configuration. (b) Proposed plume acquisition system.

The end result of such an application is a plume acquisition system that is faster, lighter, more reliable, and less costly than its current large-scale counterpart. Since the micromirrors in this system can operate in the tens to hundreds of MHz range, the image can be scanned several times and passed through a filter wheel which is added to allow for multi-spectral analysis of the image to distinguish targets.

On the Insertion of MEMS into Space Systems

Despite the tremendous advantages of MEMS devices, namely the potential to provide dramatic reductions in the size, weight, and power required for space systems, there is little acceptance presently for their application. The primary barriers are the relative immaturity of the technology, the novelty of MEMS, and lack of reliability information on these devices in a space environment. Space systems are notoriously conservative, a paradigm which initiatives such as the NASA New Millennium Program are attempting to shatter. Phillips Laboratory recently commissioned the development of a new series of satellites, called MightySat, to examine new technologies in spaceflight. PL/VTE has established a small but comprehensive payload, currently under development, including a sub-experiment for exploring MEMS technologies. In doing this, it was discovered that despite the large variety of MEMS devices in development and in the literature, that relatively few were ready for simple insertion in a non-critical experimental payload, much less a space system with a critical mission to perform. This finding attests to the present developmental state of MEMS technology. Clearly, given this finding, a relatively sparse database on MEMS reliability exists. Under normal conditions, space systems are hesitant to fly technologies that do not have a considerable maturity and experience base, making insertion of MEMS even more difficult. In an attempt to "short-circuit" some of these issues, PL/VTE is establishing experimental space insertions of MEMS technologies, based on devices developed not only from internal and joint programs, but from commercial sources as well. It is believed that in this manner, by establishing a continued series of space insertion opportunities, it will be possible to establish an early

database on reliability, which, in conjunction with other on-going initiatives in reliability, will accelerate the pace of insertion of viable MEMS-based components and modules into space systems.

Reliability

A primary concern for the use of MEMS in space systems is the reliability of the devices. To better understand fundamental reliability issues, Failure Analysis Associates has been conducting a \$1.14 million research effort under ARPA funding to study the failure mechanisms of MEMS devices. Among the most significant failure modes are fractures due to actuation beyond the active range of the device and various fabrication impurities that can increase the likelihood of a particular failure. Figure 6 illustrates the effect of fabrication errors on the structure of a device. The circles highlight the areas where the support structure and the active grid of the device are poorly formed due to any one of several steps in fabrication.

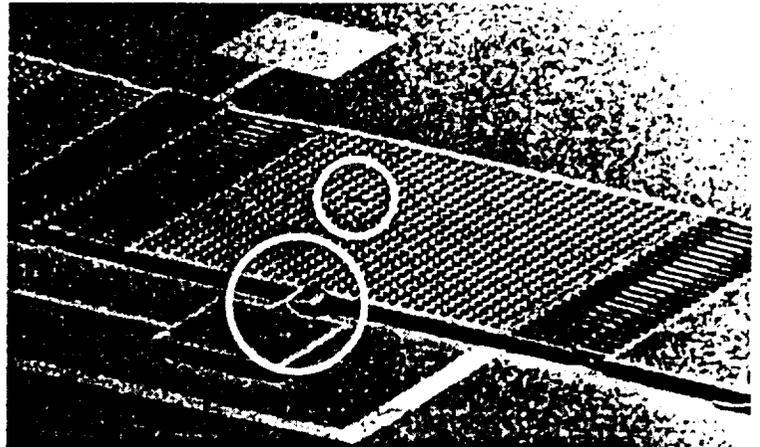


Figure 6. Example of Device Fabrication Errors (photograph from Failure Analysis Associates).

The primary purpose of the research is to reduce the likelihood of failures or the possibility of failures without the need to completely inspect every MEMS device under consideration for space systems applications. The goal of the failure mode analysis is either to show that the most significant of the feasible modes will most likely not cause failure during the mission of interest or that the effect or probability of any given failure mode can be reduced by making improvements in the fabrication process.

MAPLE: A Fledgling Space Experiment Series

The purpose of the Microsystem And Packaging for Low-power Electronics (MAPLE) experiments is to demonstrate aggressive new approaches in electronics, advanced packaging, and MEMS as enablers for next-generation spacecraft. It provides the opportunity for heritage and in-situ reliability instrumentation of controversial new technology components. It also provides the opportunity to examine new semiconductor processes and circuit designs that achieve low power operation and how they will operate in a space environment. The MAPLE concept is a “basket” experiment, based on a collection of subexperiments pertaining to advanced microelectronics, MEMS, and advanced packaging. MAPLE payloads are designed as a low-weight and relatively low power payload (usually under 8W and five pounds).

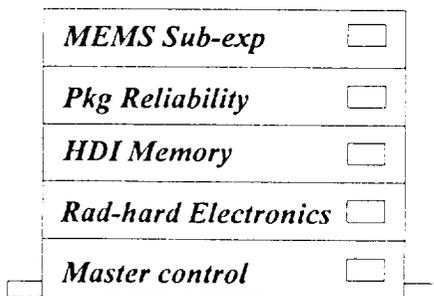


Figure 7. Simplified MAPLE payload.

Presently, most MAPLE configurations consists of four sub-experiments and experiment master controller (Figure 7). Each subexperiment contains a low-power dedicated microcontroller and serial interface to a central master controller. Although MAPLE appears to be a single chassis, the subexperiments are built as separate slices and stacked into one assembly. Alternately, the slices may be physically distributed throughout the satellite structure. In some cases, it is conceivable that two or even three copies of the same MAPLE experiment could be integrated in a given satellite, providing the ability to generate more statistics on selected components.

By establishing an indigenous space experiment payload development program, several test flights have been scheduled over the next few years to establish reliability and operating statistics for MEMS devices in space. The first efforts are the Mighty-Sat launch scheduled for delivery in March 1996 and flight in December 1996, and the Space Test Research Vehicle (STRV-2) which is scheduled for delivery in June 1996 and flight in March 1997. Both will carry MEMS-based accelerometer devices. Originally, it was felt that more devices would be available for these initial missions, but most devices examined were not in a condition where spaceflight would be practical.

The Mighty-Sat test flight will carry Analog Devices' ADXL-02 and ADXL-05 chips, arranged as orthogonal, three axis sets. The ADXL-05 device may well constitute the only MEMS devices that has received any previous exposure to spaceflight.¹¹ For the sake of expeditiousness, conventional packaging approaches were required, hence the true miniaturized potential of MEMS devices will not be realized in these initial experiments (photomicrographs of the devices are shown in Figure 9). The primary mission of this test flight is to the performance of representative MEMS devices in the space environment. One set of accelerometers will be placed in close proximity to a panel containing explosively released bolts and non-explosive shaped-based memory equivalents. In addition to monitoring these events, a conventional "doorbell"-type solenoid actuator will be attached to one accelerometer cluster to provide additional mechanical stimulation for the purpose of extensive self-testing procedures.

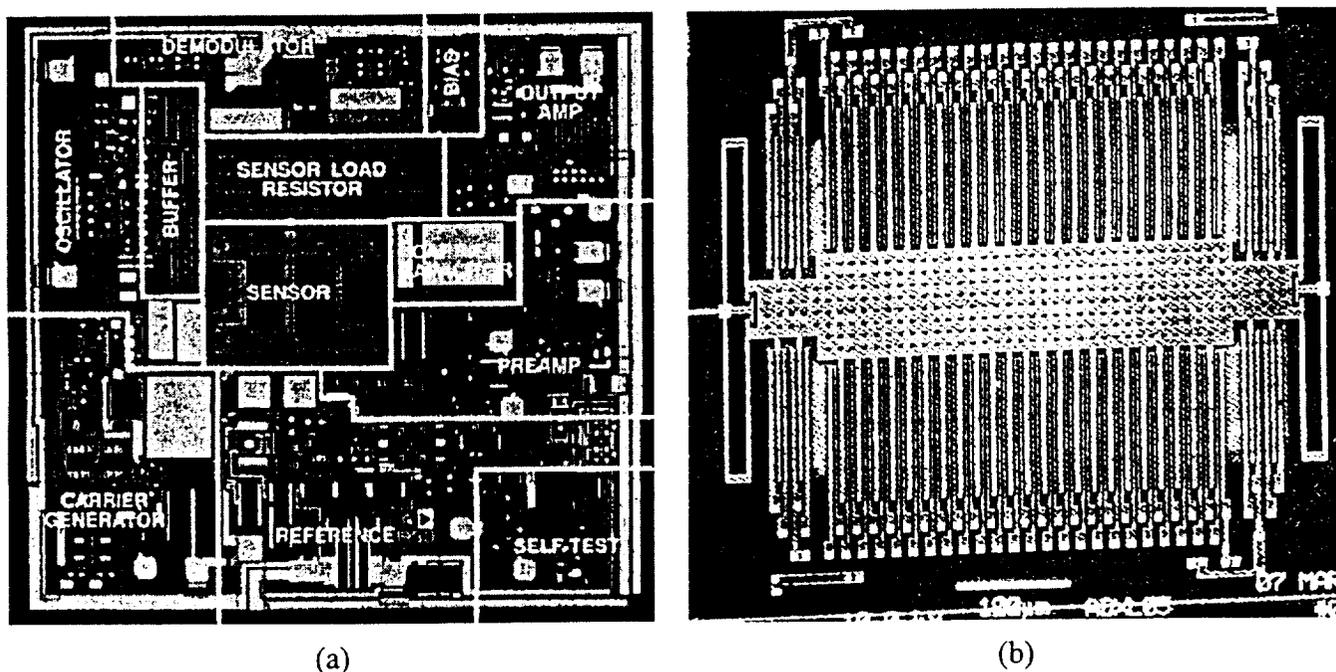


Figure 9. Analog Device commercial MEMS-based accelerometers. (a) ADXL-50 die¹². (b) Close-up of sensor portion of ADXL-05 die¹³.

Initial low-dose rate ionizing radiation tests were performed on the ADXL-50 in the PL/VTE Cesium chamber, which was biased and calibrated before and after exposure with available vibration tables. The first test was terminated after 5,000 rads dose accumulation, as predicted by the apparatus dosimeter. No changes in performance were found, and more testing is planning to predict and simulate potential on-orbit degradation modes¹⁴.

The STRV-2 test flight will carry the ADXL-05 in a configuration similar to that used in Mighty-Sat. Additionally, the performance of a unique and very sensitive accelerometer developed by the Jet Propulsion Laboratory based on tunneling effects will be examined¹⁵. In tandem, the two classes of MEMS accelerometers will provide a large dynamic range of response in vibration. Furthermore, the

STRV-2 orbit is highly elliptic and will consequently present a much more severe radiation environment for the devices. If successfully completed and launched, both MAPLE experiments will provide early windows on the performance of at least two types of MEMS devices. Follow-on MAPLE experiments are planned, and the prospects of obtaining a greater variety of MEMS devices for these missions are encouraging.

Conclusions

Microelectromechanical Systems (MEMS) has become the latest technology to expand the range of operation of standard mechanical systems. Boasting such advantages as dramatic reductions in size, weight, cost, and failure rate, MEMS devices have proven their potential to effectively address a wide variety of modern applications. As a means of continuing this trend, MEMS is being considered for use in space systems in which the advantages of such devices are of specific interest. It is of the greatest concern that the cost of launching space systems be minimized and the reliability of such systems be maximized. These inherent abilities of MEMS devices lend themselves favorably to such applications in which the overall weight of a given system can be reduced by several orders of magnitude while simultaneously improving reliability.

In this paper, several current research endeavors were presented which seek to utilize these characteristics of MEMS devices for space systems. Each of these are expanding on the operational limits of standard systems such as accelerometers and inertial sensors. Additionally, other research topics are discussed which are projected for future applications. These topics are currently under consideration and planning for research in the near future.

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